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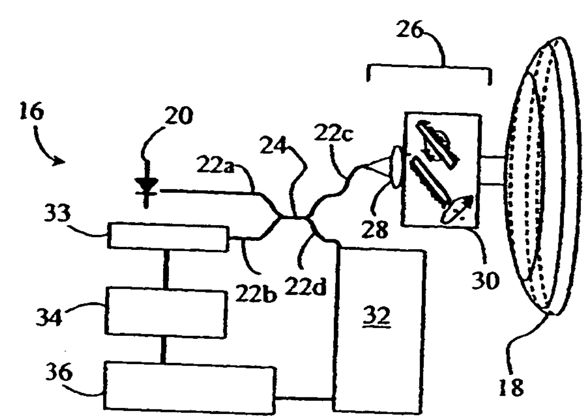
(54) Title: CLOSED LOOP OPTICAL COHERENCE TOPOGRAPHY



(57) Abstract: The present invention provides an optical coherence topography apparatus and method for determining the topology of a surface of or within a sample, the apparatus having: a light source for providing a beam of light; a beam splitter for splitting the beam into first and second components; a sample arm for receiving the sample and characterized by a first path length; scanning means for scanning the sample with the first component of the beam; a reference arm with a reference means for receiving the second component, the reference arm characterized by a second path length; and a light detector for detecting interference patterns due to interference of a reference beam from the reference means and a sample beam from the sample; wherein one of the first and the second path lengths is controllably adjustable and the apparatus includes control means responsive to changes in the interference patterns due to differences in the first path length as the sample is scanned, by adjusting the one of the first and the second path lengths to compensate for the changes in the first path length, whereby the adjustment in the one of first and second path lengths is indicative of the changes in the first path length and thereby of the topology.

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CLOSED LOOP OPTICAL COHERENCE TOPOGRAPHY

The present invention relates to the field of optical coherence topography, of particular but by no means exclusive application in the area of corneal topography.

Existing Optical Coherence Tomography (OCT) has been used widely for creating three dimensional images of (especially) biological samples, and has found widespread application in the imaging of the cornea and other structures in the human eye. OCT is a non-intrusive technique, it has a dynamic range that can exceed 100 dB and - importantly for ophthalmic applications - it performs well with dry eyes, from which scattered light can be detected with a good signal to noise ratio.

However, conventional OCT systems generate volume rather than surface maps, as they detect light scattered from a series of depths in the Z-axis as the reference mirror of the OCT interferometer is correspondingly scanned along its Z-axis. The actual depth within the sample of a feature is determined from the Z coordinate of the scanned reference mirror at the time of detection. Detected features may be on the surface of the sample or, if the incident light can penetrate the sample (as is the case with many biological samples), within the sample. In either case, a large three dimensional data cube must be collected even though, in many applications, a surface topology is all that is of interest. The resolution of the three dimensional data is ordinarily limited by the coherence envelope (typically 10 to 20 μm).

This large OCT data set or "volume map" must then be analyzed to extract the desired information, a lengthy data reduction task. For example, if the sample is corneal tissue, the results of an OCT scan will reveal the transitions or boundaries between layers of differing

refractive index. The most significant of these will be between the air and the cornea itself, so extracting the three dimensional location of this boundary is equivalent to generating, from the original volume map, a surface map of the cornea.

Figure 1 is a perspective view of the volume map 10 of OCT data that would be collected in order to obtain a surface map 12 of a cornea 14, which surface map 12 represents a small subset of the volume map 10.

Thus, this technique is slow as a complete volume scan must first be performed - during which the sample must remain essentially motionless - and then the data set must be reduced to extract the desired information. This effectively eliminates this technique as a real-time observational tool during, for example, surgery, as real-time surface profiling of macroscopic biological objects such as the human cornea must avoid motion artefacts occurring on time scales of order ten milliseconds. The sample - such as an eye - may be difficult to immobilize, and the available computing resources may not be adequate to reduce the vast volume data set sufficiently quickly.

It is an object of the present invention, therefore, to provide an OCT system that eliminates the need to collect the volume data set, by compensating for movement in a surface of a sample and collecting data only at that surface. Such a surface may be the external surface, or - in some applications - a surface defined by the boundary between two layers within the sample. In one aspect of the invention, it is an object to provide such a system with resolution sufficient for the measurement of corneal topography.

According to the present invention, therefore there is provided an optical coherence topography apparatus for

determining the topology of a surface of or within a sample, having:

a light source for providing a beam of light;

a beam splitter for splitting said beam into first and second components;

a sample arm for receiving said sample and characterized by a first path length;

scanning means for scanning said sample with said first component of said beam;

a reference arm with a reference means for receiving said second component, said reference arm characterized by a second path length; and

a light detector for detecting interference patterns due to interference of a reference beam from said reference means and a sample beam from said sample;

wherein one of said first and said second path lengths is controllably adjustable and said apparatus includes control means responsive to changes in said interference patterns due to differences in said first path length as said sample is scanned, by adjusting said one of said first and said second path lengths to compensate for said changes in said first path length, whereby said adjustment in said one of first and second path lengths is indicative of said changes in said first path length and thereby of said topology.

The light source may comprise a broadband source of low coherence light or a narrowband source. A broadband source has a short coherence function, which therefore 'gates' the region from which reflections may be detected.

Preferably one of said first and second path lengths is said second path length, and said control means is operable to adjust said second path length by controlling said reference means.

The control means may be operable to adjust said first path

length, such as by moving said sample or, where said sample arm includes an optic fibre, stretching said optic fibre.

Thus, the topology of the sample can be deduced from the degree, at any point in the scanning of the sample, that the first or second path length is adjusted to compensate for variations in the first or sample arm path length due to that topology. Although this would be of principal application in determining the surface topology of a sample, if the sample transmits sufficient light, it may also be possible to detect and determine the topology of an internal surface or boundary.

The scanning means is preferably operable for scanning the sample in two orthogonal axes perpendicular to the direction of the first component of the beam.

The beam splitter may comprise a partially silvered mirror or, preferably, an optical coupler such as a fused biconical taper coupler.

Preferably said light source is a superluminescent diode or other broad bandwidth source. The light source may be an incandescent source, a mode-locked laser or a narrowband continuous wave laser.

Preferably said reference arm includes an optical delay line, including dispersing means (such as a diffraction grating) for dispersing light received by said reference arm and a reflecting means with adjustable tilt for receiving light from said dispersing means and introducing a path difference according to said tilt.

In one embodiment said optical delay line is operable to decouple phase and group delay so that said phase delay can be used to provide a control signal and said group delay can be used to gate the zone from which a reflection can be

received.

Alternatively, the optical delay line may be implemented using acousto-optic or electro-optic devices.

In one specific embodiment said light source comprises a narrowband laser and said reference arm includes an optical delay line, said delay line includinga reflecting means with adjustable tilt for introducing a path difference according to said tilt.

The reflecting means may comprise any suitable mirror or prism (such as a 90° retro-reflector prism).

According to the present invention, there is also provided an apparatus for determining the topology of a corneal surface including the apparatus described above.

The present invention further provides a method for determining the topology of a sample, comprising:

splitting a beam of light into first and second components;

scanning said sample characterized by a first path length with said first component and directing said second component to a reference means characterized by a second path length;

forming an interference pattern of light reflected by said sample and from said reference means;

detecting changes in said interference pattern due to variations in said first path length due to said topology of said sample;

adjusting one of said first and second path lengths to compensate for said changes; and

determining said topology from said adjustments.

The beam of light may be a beam of low coherence light, and the beam may be a narrowband beam of light.

Preferably said one of said first and second path length is said second path length.

Preferably said adjusting of said second path length is by means of said reference means.

Preferably said reference means includes dispersing means for dispersing light received by said reference means, and a reflecting means with adjustable tilt for receiving light from said dispersing means and introducing a path difference according to said tilt.

In one embodiment, said method includes providing said beam of light by means of a narrowband continuous wave laser, and said reference means includes a reflecting means with adjustable tilt for introducing a path difference according to said tilt.

Preferably said scanning said sample is in a manner which minimises the rate of change of the first path length due to said topology.

Where said topology is spherical, preferably said scanning is in a spiral pattern.

The present invention still further provides a method for determining the topology of a corneal surface, said method including the method described above.

In order that the present invention may be more clearly ascertained, preferred embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of an OCT data volume map collected in order to obtain a surface map of a cornea according to a prior art technique;

Figure 2 is a schematic view of an optical coherence tomograph apparatus according to a preferred embodiment of the present invention;

Figure 3 is a schematic representation of delay line of the apparatus of figure 2;

Figure 4 is an interferogram depicting three possible interferograms from the apparatus of figure 2;

Figure 5 is a schematic view of the apparatus of figure 2 in a test configuration with a mirror as a test sample and PZT fibre stretcher for simulating variations in the path length of the sample arm;

Figures 6a, 6b and 6c are graphs of results from the test configuration;

Figure 7 depicts a preferred scanning pattern for the apparatus of figure 2;

Figure 8 is a schematic view of a typical post-cut or operative) corneal profile; and

Figure 9 depicts the path that the tracking system would need to follow if the corneal profile in figure 8 were traced using the spiral of figure 7.

An optical coherence tomography apparatus according to a preferred embodiment of the present invention is shown generally at 16 in figure 2, for determining the topology of a sample, for example cornea 18. A broadband light source in the form of superluminescent diode 20 illuminates a fibre-based Michelson interferometer, including optic fibres 22a,b,c,d, optical coupler 24, sample arm 26 (including focussing lens 28 and orthogonal scanners 30), reference arm 32 and detector 33.

The detector 33 detects interference fringes only if the optical paths of the sample arm 26 and reference arm 32 match to within the coherence length of the source (~10 μm). The apparatus 16 also includes a lock-in amplifier 34 and PID controller 36. In some embodiments the lock-in amplifier 34 may not be required.

Referring to figure 3, the reference arm 32 comprises a grating-based optical delay line (ODL), which utilizes the phase delay generated by tilted mirror to generate a control signal and the group delay in combination with the coherence function of the source to gate the zone in the sample from which a reflection can be detected. The light beam entering the reference arm 32 along fibre 22d is collimated by collimator 40 and dispersed by grating 42 before passing through lens 44 and impinging upon piezo-tilted mirror 46. The mirror 46 is controlled by PID controller 36 (see figure 2). The beam then passes back through lens 44, via grating 42 to second pass mirror 48, before retracing the same optical path and exiting the reference arm 32.

Optionally, the grating 42 and lens 44 may clearly be replaced by a concave grating.

The optical phase associated with the path length of the reference arm 32 is thus adjustable, and determined by the angle of mirror 46. This piezo-tilted mirror 46 provides the phase ramp, and the angle of tilt corresponds to an effective linear translation of the mirror 46. The proportionality is set by mirror tilt angle σ and the offset of the pivot of the piezo-tilted mirror x_0 from the optical axis of the grating and lens. The path length difference so generated δ is given by

$$\delta = \sigma x_0 \ .$$

By virtue of the independence of group and phase delay in the ODL, the frequency of the interference fringes generated by altering the tilt angle σ may be up- or down-converted in a controlled way. The zero-crossing of a fringe defines the position of the sample 18. Hence, "closing the servo loop" (by means of the detector 33 to lock-in amplifier 34 to PID controller 36 to piezo-tilted mirror 46 connection shown in figure 2) allows the optical

path length of the reference arm 32 to be locked to that of the sample arm 26, which - when expressed as a function of the instantaneous position of scanners 30 - corresponds directly to the topology of the sample 18.

The operation of the grating based ODL is based on the Fourier correspondence between the phase ramp in the frequency domain and the group delay in time domain. By virtue of the decoupling of the phase and group delay, the frequency of the interference fringes is controlled by the offset x_0. Three interferograms 50 generated by scanning the tilt angle σ are shown schematically in figure 4. Complete demodulation at zero offset results in the envelope 52, which does not produce a zero crossing and therefore cannot be used as a control signal.

There are two separate essentially sinusoidal oscillations under the envelope 52: the higher frequency oscillation represents an up-converted fringe pattern 54. The lower frequency oscillation represents a down-converted fringe pattern 56. The frequency of the fringe pattern will, therefore, determine the angle of the zero-crossing point (of fringes with horizontal axis), and therefore the resolution with which this point - and therefore the sample 18 - can be located. The advantage of the adjustability of the fringe frequency is that one can trade off high stability of the apparatus (i.e. with low fringe frequency) versus high resolution (i.e. with high fringe frequency) as preferred or required.

Example

Figure 5 depicts a test arrangement of the apparatus of figure 2, where the sample is a plane mirror 60 and sample arm fibre 22c has been provided with a PZT fibre stretcher 62 for simulating variations in the path length of the sample arm 26.

For the purposes of this example, the bandwidth was about 10 Hz and the tracking range about 1 μm.

Figure 6a depicts the signal obtained without controlling the piezo-tilted mirror 46: the sample arm path length varies slowly and randomly. However, at about t = 6.8 s (indicated by 70), the closed-loop system was switched on and the sample arm length tracked by the reference arm.

Next, PZT fibre stretcher 62 was driven with a saw-toothed signal 64 to effect an optical path variation in the sample arm 26: the effect on the position of the sample 60 is shown in figure 6b, where the corresponding movement of the sample is clearly visible.

Finally, the closed-loop system was introduced; the resulting, compensating error signal (which should be the exact opposite of the variation in the sample arm path length) is shown in figure 6c. As expected, the error signal closely mirrors that variation.

A resolution of about 0.2 μm was obtained.

In corneal surgical applications, a spiral scan path (see 72 in figure 7) is preferred, so that the rate of change in the Z-axis of the sample is minimized. Some stability can then be sacrificed for improved resolution.

Figure 8 shows schematically a typical corneal profile after surgery in section. Figure 9 shows schematically the change in Z-axis coordinate of the tracking reference arm when the optical beam traces out a spiral path 72 on the cornea, plotted as delay *d* versus time *t*.

An optical coherence tomography apparatus according to an alternative embodiment, while generally similar to

apparatus 16, employs a continuous wave laser light source, and a mirror rather than a diffraction grating.

In this embodiment, however, the laser can lock on to any fringe, so if there were two reflectors in a system that both produce approximately equal signals, it may be difficult to deduce which reflector is being tracked. In the apparatus 16 (with a broadband source in the form of superluminescent diode 20) one only detects a reflection when the reflection location matches the group delay (also set by the tilt and offset) to within the coherence length, thereby discriminating other reflectors that are located more than this length from the matched location.

Modifications within the spirit and scope of the invention may readily be effected by persons skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example hereinabove.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. An optical coherence topography apparatus for determining the topology of a surface of or within a sample, having:

a light source for providing a beam of light;

a beam splitter for splitting said beam into first and second components;

a sample arm for receiving said sample and characterized by a first path length;

scanning means for scanning said sample with said first component of said beam;

a reference arm with a reference means for receiving said second component, said reference arm characterized by a second path length; and

a light detector for detecting interference patterns due to interference of a reference beam from said reference means and a sample beam from said sample;

wherein one of said first and said second path lengths is controllably adjustable and said apparatus includes control means responsive to changes in said interference patterns due to differences in said first path length as said sample is scanned, by adjusting said one of said first and said second path lengths to compensate for said changes in said first path length, whereby said adjustment in said one of first and second path lengths is indicative of said changes in said first path length and thereby of said topology.

2. An apparatus as claimed in claim 1, wherein said light source comprises a broadband source of low coherence light.

3. An apparatus as claimed in claim 2, wherein said light source is a superluminescent diode .

4. An apparatus as claimed in claim 1, wherein said light source is an incandescent source or a mode-locked laser.

5. An apparatus as claimed in claim 1, wherein said light source comprises a narrowband laser source.

6. An apparatus as claimed in any one of the preceding claims, wherein one of said first and second path lengths is said second path length, and said control means is operable to adjust said second path length by controlling said reference means.

7. An apparatus as claimed in any one of the preceding claims, wherein said control means is operable to adjust said first path length.

8. An apparatus as claimed in claim 7, wherein said control means is operable to adjust said first path length by moving said sample or, where said sample arm includes an optic fibre, stretching said optic fibre.

9. An apparatus as claimed in any one of the preceding claims, wherein said scanning means is operable for scanning the sample in two orthogonal axes perpendicular to the direction of the first component of the beam.

10. An apparatus as claimed in any one of the preceding claims, wherein said beam splitter comprises a partially silvered mirror.

11. An apparatus as claimed in claim 10, wherein said beam splitter comprises an optical coupler.

12. An apparatus as claimed in any one of the preceding claims, wherein said reference arm includes an optical delay line, including dispersing means for dispersing light received by said reference arm and a reflecting means with adjustable tilt for receiving light from said dispersing means and introducing a path difference according to said

tilt.

13. An apparatus as claimed in claim 12, wherein said reflecting means comprises any suitable mirror or prism.

14. An apparatus as claimed in either claim 12 or 13, wherein said optical delay line is operable to decouple phase and group delay so that said phase delay can be used to provide a control signal and said group delay can be used to gate the zone from which a reflection can be received.

15. An apparatus as claimed in any one of claims 1 to 11, wherein said reference arm includes an optical delay line implemented using acousto-optic or electro-optic devices.

16. An apparatus as claimed in claim 1, wherein said light source comprises a narrowband laser and said reference arm includes an optical delay line, said delay line including a reflecting means with adjustable tilt for introducing a path difference according to said tilt.

17. An apparatus for determining the topology of a corneal surface including the optical coherence topography apparatus as claimed in any one of the preceding claims.

18. A method for determining the topology of a sample, comprising:

splitting a beam of light into first and second components;

scanning said sample characterized by a first path length with said first component and directing said second component to a reference means characterized by a second path length;

forming an interference pattern of light reflected by said sample and from said reference means;

detecting changes in said interference pattern

due to variations in said first path length due to said topology of said sample;

adjusting one of said first and second path lengths to compensate for said changes; and

determining said topology from said adjustments.

19. A method as claimed in claim 18, wherein said beam of light is a beam of low coherence light.

20. A method as claimed in claim 18, wherein said beam is a narrowband beam of light.

21. A method as claimed in any one of claims 18 to 20, wherein said one of said first and second path length is said second path length.

22. A method as claimed in any one of claims 18 to 21, wherein said adjusting of said second path length is by means of said reference means.

23. A method as claimed in any one of claims 18 to 22, wherein said reference means includes dispersing means for dispersing light received by said reference means, and a reflecting means with adjustable tilt for receiving light from said dispersing means and introducing a path difference according to said tilt.

24. A method as claimed in claim 18, wherein said method includes providing said beam of light by means of a narrowband continuous wave laser, and said reference means includes areflecting means with adjustable tilt for introducing a path difference according to said tilt.

25. A method as claimed in any one of claims 18 to 24, wherein said scanning said sample is in a manner that minimises the rate of change of the first path length due to said topology.

26. A method as claimed in claim 25, wherein, where said topology is spherical, said scanning is in a spiral pattern.

27. A method for determining the topology of a corneal surface, said method including the method for determining the topology of a sample as claimed in any one of claims 18 to 26.

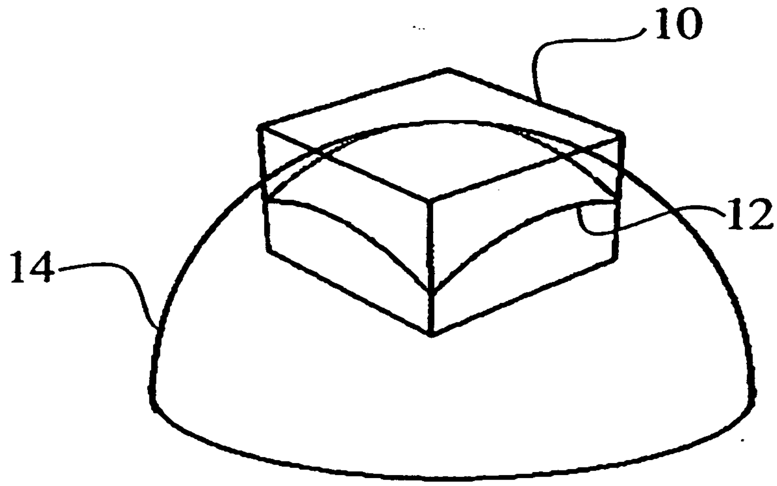

Figure 1

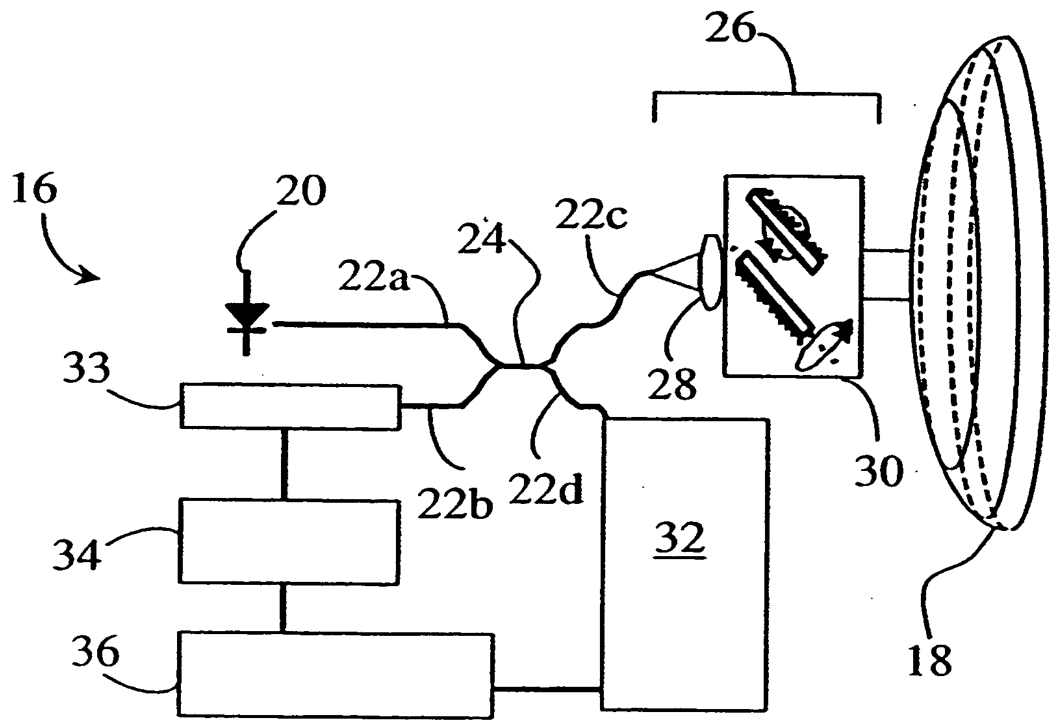

Figure 2

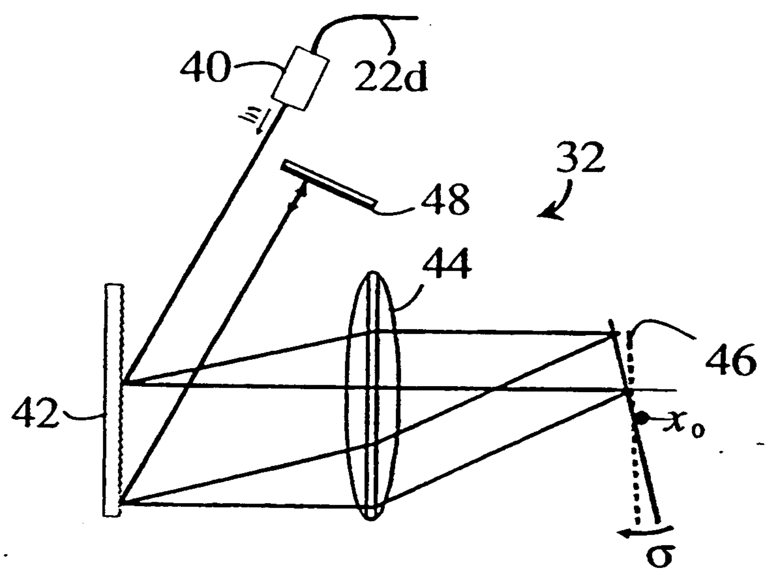

Figure 3

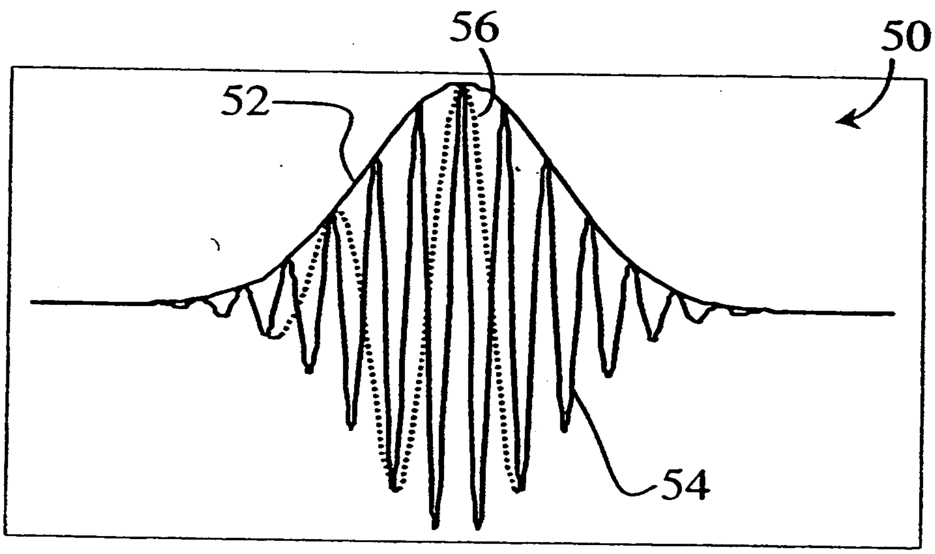

Figure 4

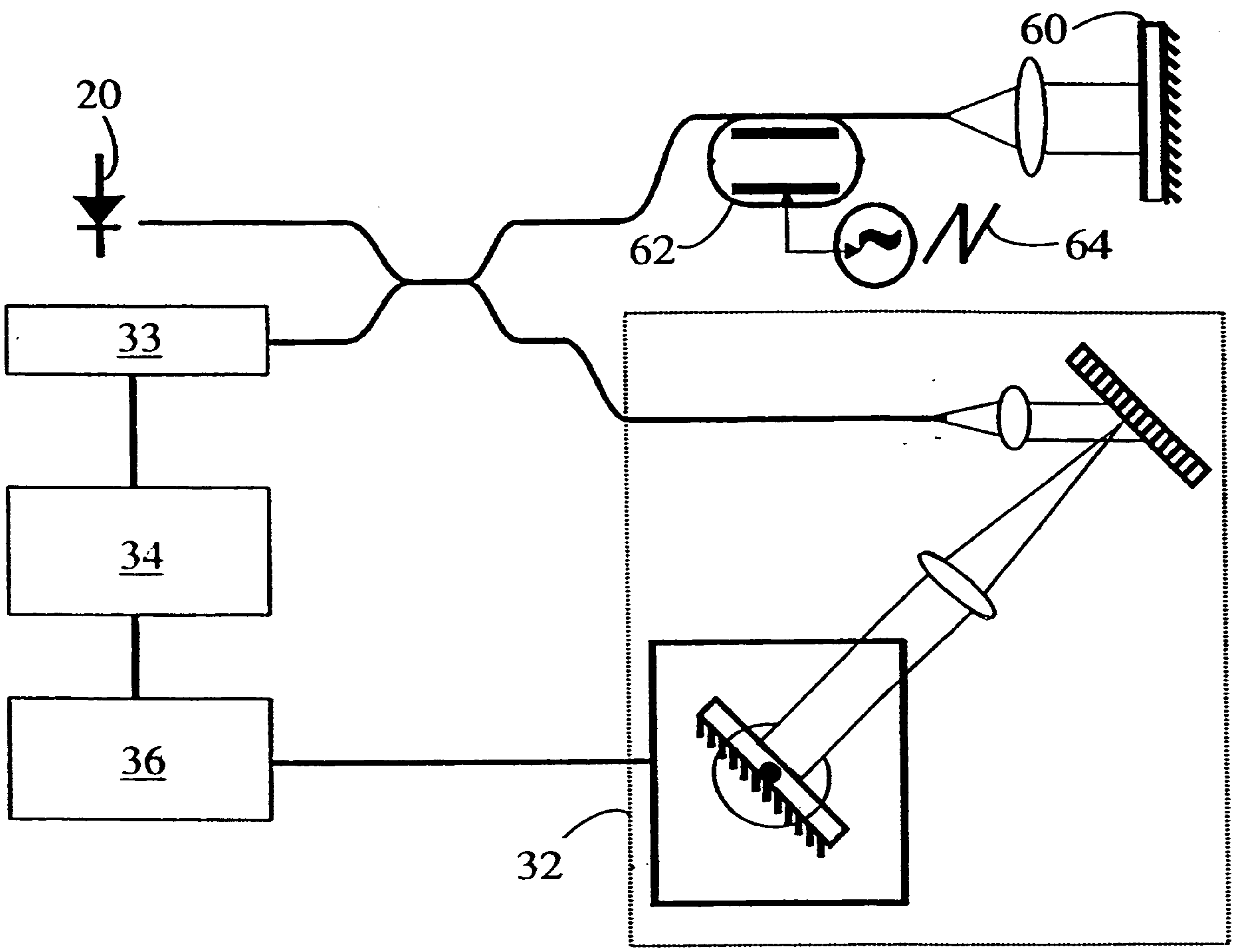

Figure 5

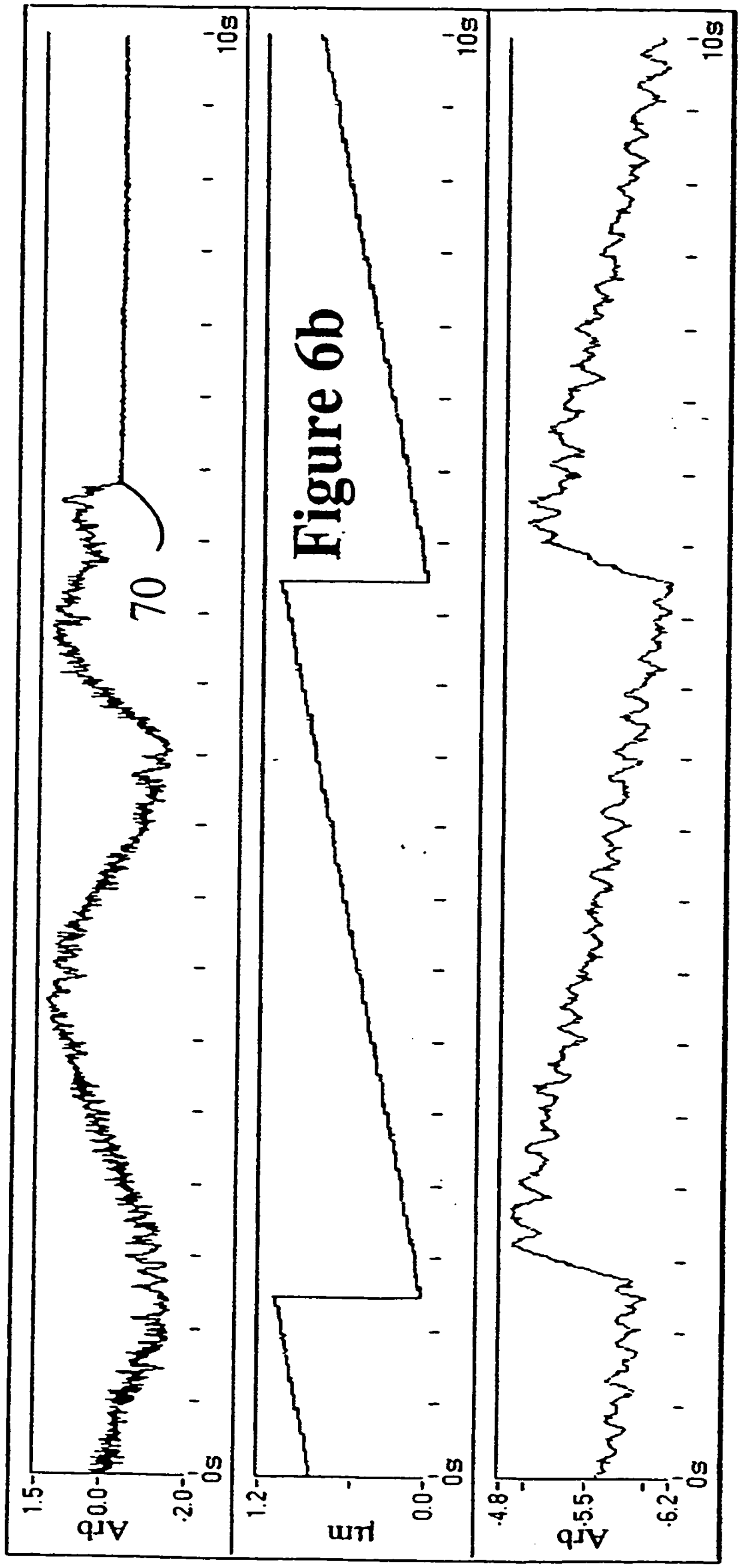

Figure 6a

Figure 6b

Figure 6c

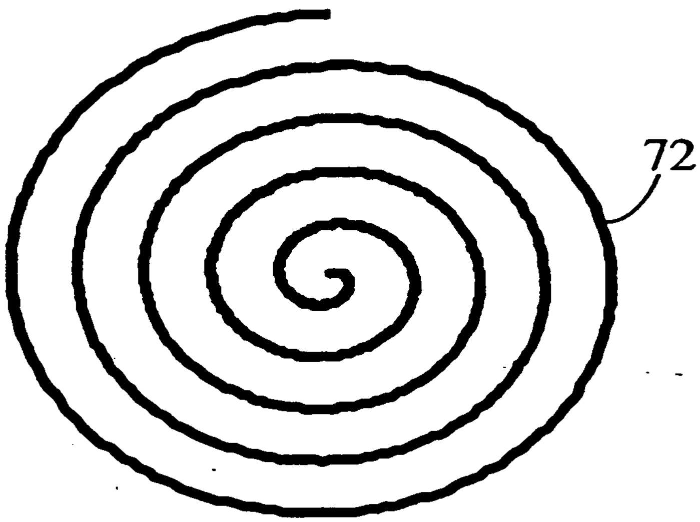

Figure 7

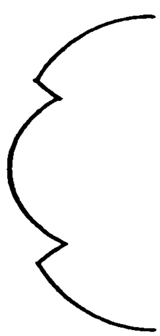

Figure 8

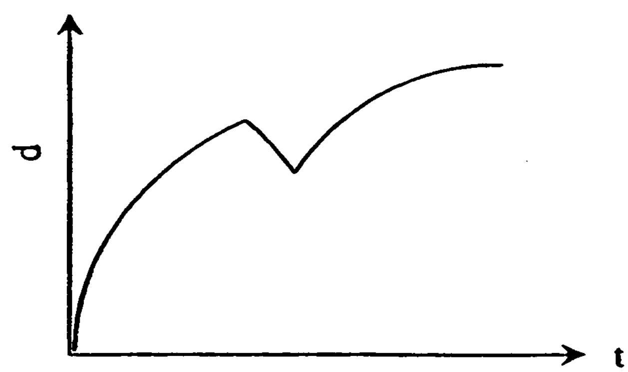

Figure 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU00/00802

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. [7]: A61B 3/107 G01B 11/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B 3/-, G01B 11/-

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99/01716 A (MACPHERSON) 14 January 1999	
A	WO 94/18521 A (ZYGO CORPORATION) 18 August 1994	
A	WO 94/18523 A (ZYGO CORPORATION) 18 August 1994	

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

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Date of the actual completion of the international search 8 September 2000	Date of mailing of the international search report 13 SEP 2000
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer B Bourke BRENDAN BOURKE Telephone No : (02) 6283 2148

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU00/00802

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Patent Document Cited in Search Report		Patent Family Member			
WO	9901716	AU	82743/98		
WO	9418521	EP	682771	US	5398113
WO	9418523	EP	746745	US	5402234

END OF ANNEX